Supernovae and Their Consequences:

Studies with the *Generation-X* Mission

Science Working Paper for the 2010 Decadal Survey

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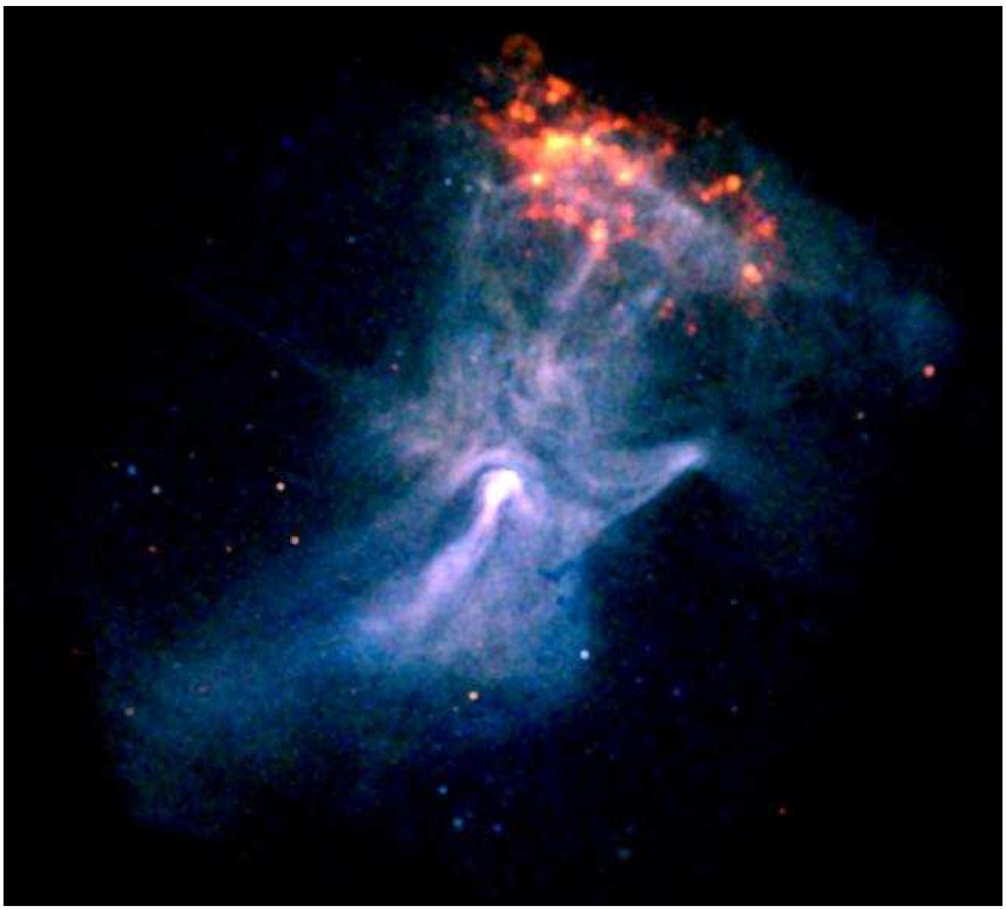

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1. Introduction: Supernovae and Their Remnants at High Resolution

Supernovae (SNe) and their by-products play central roles in the chemical evolution of their host galaxies, the acceleration of cosmic-rays, and the formation of compact objects with the most extreme densities and magnetic fields observed in nature. Their use as cosmological yardsticks, estimators of neutron star birth rates, benchmarks for stellar explosion models, and observable sites of energetic shocks – both relativistic and non-relativistic – place these objects as crucial to our understanding of a broad range of astrophysically important phenomena. X-ray observations play a particularly important role in revealing the underlying physics of supernovae, their ejecta-rich remnants, and the energetic pulsars and their winds.

From the identification in supernova remnants (SNRs) of thin nonthermal filaments and discrete variations of ejecta material that point to asymmetries in the associated explosions, to direct imaging of the jets and wind termination shocks in pulsar wind nebulae, high resolution X-ray imaging accompanied by spatially-resolved spectroscopy has revolutionized our view of these objects. But there remain a large number of unsettled questions for which current observational capabilities, while providing partial answers or clear directions toward these answers, are insufficient. Extending current capabilities to higher sensitivity and spectral resolution will address many of these questions, making studies of supernova remnants with the International X-ray Observatory (*IXO*) particularly important and promising. But some of the current questions will find their answers only by going beyond the sensitivity provided by *IXO* and the angular resolution provided by *Chandra*. As we describe below, such fundamental issues as the nature of the progenitors of Type Ia SNe, the particle distribution function produced in cosmic-ray modified shocks, and the conversion of pulsar spin-down energy into an expanding magnetic bubble of relativistic particles require the capabilities being developed for the *Generation-X* (*Gen-X*) mission. With goals of $0.1''$ angular resolution, $\sim 50\ \mathrm{m}^2$ collecting area, and 2 eV spectral resolution, *Gen-X* will probe emission and shock structures whose properties are crucial for our understanding of supernovae and their remnants, as well as a broad range of themes in high-energy astrophysics.

2. Pulsars and Their Winds

Chandra images and spectra of a handful of pulsar wind nebulae have revealed stunning examples of jets and shock-bounded outflows. Imaging of Galactic PWNe at higher sensitivity and resolution will reveal the manner by which the rotational energy of a rapidly-spinning neutron star is converted into an expanding bubble of energetic particles and magnetic flux, accompanied by energetic jets, and how these particles escape to ultimately enhance the energy density of the Galaxy.

Timing studies of pulsars provide a direct measure of their spin-down behavior, leading to a simple picture in which the observed radiation results from the slow sacrifice of rotational kinetic energy from the rapidly-spinning, highly magnetic stars. The actual life cycle of this rotational energy is poorly understood, however. Multiwavelength observations, culminating with those by *Chandra*, have led us to understand that rapidly-rotating neutron stars generate winds composed of particles and magnetic flux, and that these winds expand to form nebulae that are bound by the surrounding medium into which they expand – typically slow-moving supernova ejecta at early ages (for a review, see Gaensler & Slane 2006).

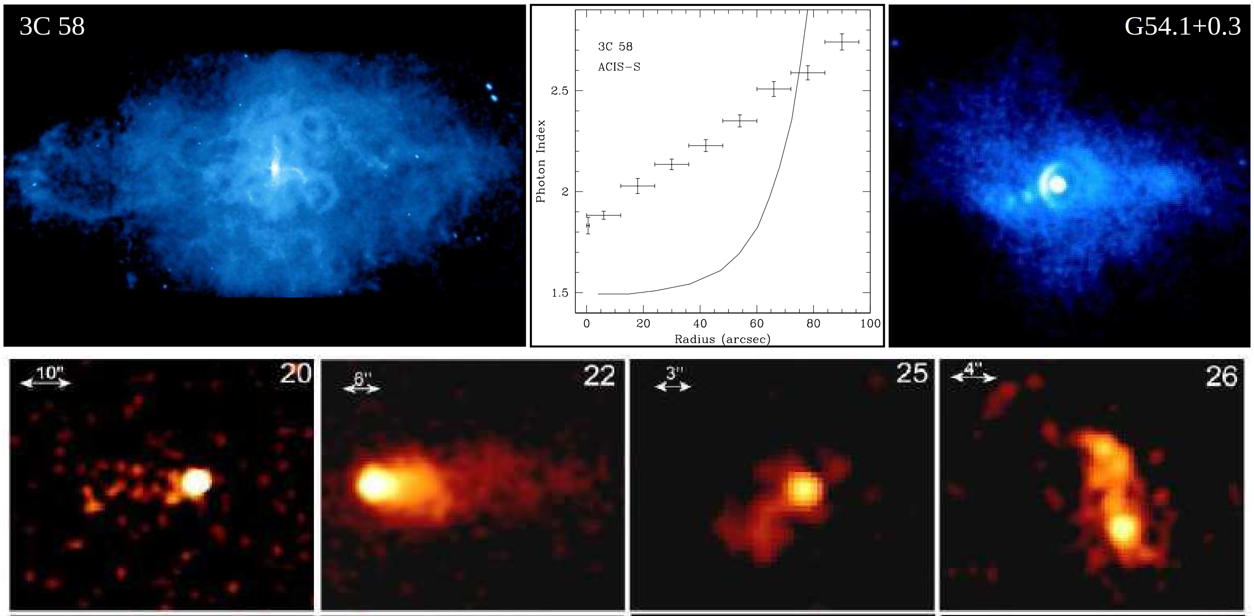

Fig. 1.— *Chandra images showing small-scale structure in the wind termination shock region immediately surrounding the pulsars, as well as jet outflows and other complex emission structures. The radial variation in spectral index for 3C 58 (top center) and other PWNe are in considerable conflict with predictions from simple MHD models (solid curve). Chandra observations reveal extended cores and jet-like outflows for a large number of faint systems (bottom panels).*

High resolution X-ray images of several PWNe (Figure 1) reveal the sites at which the free-flowing pulsar wind interacts with the more slowly expanding nebula to form a distinct termination shock, and where jets form along the pulsar spin axis. Direct observations thus reveal the system geometry, and brightness variations from Doppler beaming provide measurements of outflow speeds (see G54.1+0.3 in Figure 1 for an example; Lu et al. 2002). The brightness of small-scale structures in the inner nebula are observed to vary with time in several systems (Hester et al. 2002, Gaensler et al. 2002), indicating instabilities in the outflows. Variability of the brightness and geometry of the jets may be the result of kink instabilities (Pavlov et al. 2003) that may also explain small-scale loop-like structures observed in some nebulae such as 3C 58 (Slane et al. 2004; see Figure 1 above). The size-scale for the termination shock and other small-scale structures in the PWN interior is of order ~ 0.1 pc or less in many of these systems, rendering them just barely resolved with *Chandra*.

The position of the termination shock identifies the site where ram-pressure from the wind is balanced by the particle and magnetic pressure in the nebula, and this, along with the X-ray luminosity, constrains the ratio of particle to magnetic energy density of the downstream wind. Coupled with the spin kinetic energy and surface magnetic field, known from timing studies, these PWNe provide the most complete systems for which we can study the full evolution of the energy budget (Reynolds & Chevalier 1984). The spin-down power injected by the pulsar, coupled with adiabatic and radiative losses, determines the evolution of the particle spectrum that dominates the energy content of the nebula. The eventual escape of these particles contributes to the overall energy density of the interstellar medium and may be responsible for local enhancements in the energetic electron/positron spectrum (Adriani et al. 2008, Chang et al. 2008).

Observations of a small number of PWNe for which current capabilities can provide sufficient sensitivity and angular resolution show that while our overall picture of PWN structure is supported, there are significant discrepancies between their predicted and observed spectral evolution. For example, the observed radial variation in spectral index (Figure 1, top center) is not consistent with simple radial streaming of the nebula particles, as assumed in most MHD models of these systems (Reynolds 2003). Simulations suggest that the flows may be much more complex, with backflows and reversals producing mixtures of particles of different ages at the same radii. We observe evidence for complex structure in some PWN interiors that may be related to instabilities that produce and regulate such mixing, but higher sensitivity observations of more systems are required to disentangle the flow patterns and constrain the underlying structure. The age of a fluid parcel can be revealed by the energies at which spectral steepening occurs, so high-spatial-resolution spectroscopy can map the history of the outflow, and may produce evidence for processes such as reacceleration or magnetic field reconnection that could take place on small scales.

Similarly, while observations clearly reveal evidence for the wind shock region in a large number of PWNe, theoretical work on the physics of relativistic shocks challenges our picture; simulations indicate that perpendicular shocks do not accelerate particles, yet in PWNe the wind shocks are thought to be perpendicular to the magnetic field everywhere. Characterization of the particle spectrum and flow properties on very small scales in the region of the termination shock is required to understand how these shocks work. Spatially resolving the shocks and interior structures in a large number of systems will be crucial to improving our understanding of the shock geometry and the acceleration efficiency – themes with broad application to extragalactic jets and GRBs as well.

While PWNe are reservoirs of the energy injected at the expense of the pulsar spin-down, the manner in which the energetic particles eventually escape from the system is not clearly understood. At late times, when the magnetic field has become weak and easily disrupted, the particle population can begin to diffuse into the surrounding ISM. However, at early times, prior to significant adiabatic losses, the toroidal magnetic field structure restricts such diffusion. However, interactions of the PWN with the SNR ejecta can result in Rayleigh-Taylor instabilities that form radial filaments. These filaments may provide regions of radial magnetic field along which energetic particles can escape at early ages. High resolution imaging, with large collecting area, is required to investigate the PWN/ejecta interface in order to place constraints on the scale of such structures, and their contribution to particle diffusion.

With *Chandra*, we are limited to detailed studies of only a half-dozen or so of these sources, and these examples have revolutionized our understanding of PWNe. Yet *Chandra* has also revealed clear evidence of jet/torus structures in another 40-50 PWNe (Figure 1, bottom), characterized by a wide range of ages and spin-down energies (Kargaltsev & Pavlov 2008). These sources are a factor of several times smaller than the prominent PWNe studied with *Chandra*, and factors of nearly a hundred fainter. While *IXO* will contribute significantly to our understanding of the extended nebular structure for some of these PWNe – including the effects of synchrotron losses on the X-ray spectrum, and the expansion velocity of the swept-up ejecta – the detailed structure that reveals the pulsar geometry, the shock sites, and the instability regions require increases in sensitivity and angular resolution that can be provided by *Gen-X*.

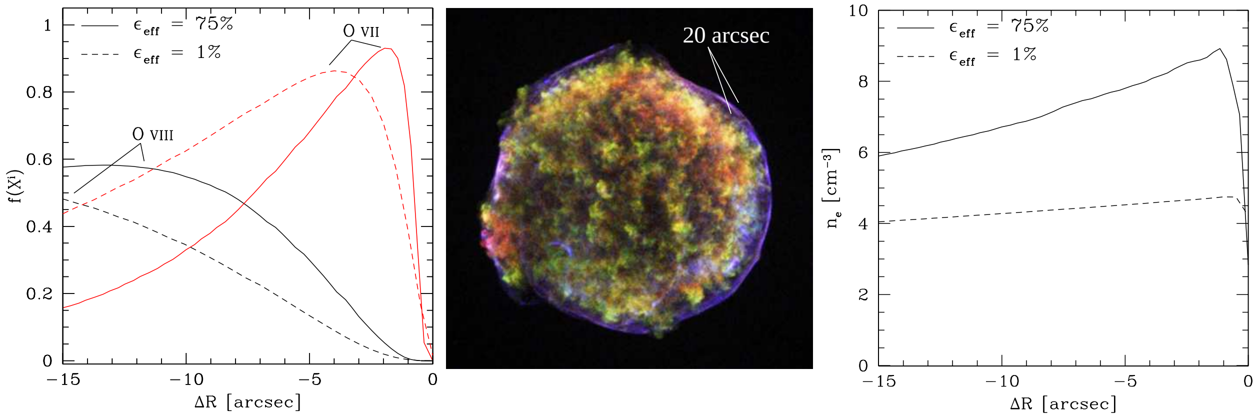

Fig. 2.— *Simulated values for the ionization fraction for O VII and O VIII (left) and the electron density (right) for regions just behind the shock in a Type Ia SN (assuming $E = 10^{51}$ erg, an ejecta mass of 1.4 $M_\odot$, an ambient density of 1 cm^{-3}, an age of 1000 yr, and a distance of 1 kpc). Solid curves correspond to cases with very efficient particle acceleration at the shock, while dashed curves represent essentially no acceleration. The approximate size scale for these plots is indicated on the Chandra image of Tycho's SNR (center), which also reveals the thin (blue) rims of nonthermal emission.*

3. Supernova Remnants: Progenitors, Process, and Particle Acceleration

3.1. Shocks and Particle Acceleration in SNRs

High-resolution imaging and spectroscopy of nearby SNRs will address crucial issues in shock physics. Studies of nonthermal filaments along with postshock temperature and ionization structure on small scales will constrain the physics of shock acceleration. Coupling expansion studies with spectral line diagnostics will provide constraints on electron-ion equilibration timescales in fast shocks.

X-ray observations over the past decade have clearly established the fact that SNR shocks are capable of accelerating particles to very high energies. Observations of thin synchrotron rims at the forward shocks of young SNRs (Figure 2) provide constraints on magnetic field amplification and on the maximum energy of the particles, as well as on the effects of particle acceleration on the shock dynamics. As the rapid expansion of an SNR drives a fast shock into the surrounding medium, resulting in compression and heating of the gas, the process of efficient particle acceleration can have a significant effect on the dynamics of the shock. The temperature of the postshock gas will be considerably lower if a significant fraction of the shock energy is efficiently directed into the nonthermal particle population. This lower temperature will result in a higher density in the postshock region as well, an effect that will produce more rapid ionization of the gas. The nonthermal particles will produce synchrotron radiation in the presence of the ambient magnetic field.

High resolution X-ray spectra provide unique temperature and density diagnostics that characterize the electrons in the postshock region, and also provide a measure of the ionization state of the gas. In Figure 2 (left panel) we show the evolution of the ionization state for O VII and O VIII as a function of distance behind the forward shock based on simulations of a 1000 year-old Type Ia SNR expanding into an ambient density of $1\ \mathrm{cm}^{-3}$ at a distance of 1 kpc, for cases with high and low particle acceleration efficiency (Patnaude, Ellison, & Slane 2009). The associated variation of the postshock density is plotted in the right panel. The exceptional energy resolution provided with the calorimeter on *IXO* will allow us to measure the density and ionization state of the gas in SNRs with unprecedented accuracy, through line ratio diagnostics, and this will provide a powerful tool for characterizing the distribution of nucleosynthesis products from the explosion. As indicated above, however, in order to probe the detailed postshock evolution that allows us to measure the properties of the shocks themselves, we also need very high angular resolution.

With the high angular resolution and a large collecting area provided by *Gen-X*, spectra obtained in small radial regions behind the shock will provide direct measurements of the postshock density profile of the electrons, $n_e(r)$, as well as that for the ionization timescale of the plasma, $n_e t(r)$. Combined, these provide a direct determination of the age of the postshock gas (i.e. the time since it passed through the forward shock) in each radial region. Using the physical position of the spectral region, determined from the imaging, this then provides a velocity map for the postshock electrons. Given the high angular resolution, the velocity of the forward shock can be determined directly through expansion measurements based on observations separated by as little as one or two years. A comparison between the upstream and downstream velocities provides a direction measurement of the shock compression ratio – a factor that depends sensitively on any cosmic-ray acceleration in the shock. The cosmic-ray production derived from the compression ratio can then be compared directly with the observed nonthermal emission from the thin synchrotron rims of the remnant in order to constrain self-consistent models for cosmic-ray modified shocks (e.g. Ellison et al. 2007). The high angular resolution would also provide crucial information on the thin nonthermal rims themselves. Within this several arcsecond thick region occurs all of the acceleration and radiative cooling of the shock-accelerated TeV-energy electrons that produce the X-ray synchrotron radiation, as well as the magnetic field amplification that is so crucial to the acceleration process.

Chandra studies of Tycho's SNR (Figure 2) have already revealed spectral steepening of the nonthermal emission as a function of distance behind the forward shock, providing constraints on the structure of the magnetic field (Cassam-Chenaï et al. 2007). Based on these data, a 50 ks observation with *Gen-X* will provide 5000-count spectra from $0.1'' \times 10''$ regions behind the northwest shock region indicated in Figure 2, providing a sensitive map of the density, ionization, and velocity structure in the postshock flow. Similarly modest exposures will provide such measurements for most of the historic remnants in the Galaxy, as well as for several older remnants for which the lower shock speeds may significantly alter the particle acceleration efficiency.

Another long-standing question with regard to fast shocks is how electrons and ions reach temperature equilibrium in the postshock region. The equilibration rate based upon Coulomb collisions is readily calculable, given the density of the gas, but there is ample evidence that more rapid equilibration takes place (e.g. Rakowski et al. 2003), with T_e/T_i being a strong function of shock velocity. Such measurements are particularly difficult, however, because X-ray spectra are sensitive primarily to the electron temperature. Measurements of the ion temperature can be obtained for particular cases where Balmer emission is observed from SNR shocks evolving into partially-neutral gas (Raymond et al. 1983; Ghavamian et al. 2007), but such conditions are observed in only a small number of SNRs. With high spectral resolution X-ray measurements, however, detection of the thermal line broadening can provide the ion temperatures as well. This has been demonstrated with grating studies of SN 1006 (Vink et al. 2003), but the extended nature of SNR emission makes such grating measurements extremely difficult, and applicable to only remnants with extremely sharp features at the position of the shock. With the high spectral resolution provided by the next generation of X-ray calorimeters like that on *IXO*, however, spatially-resolved spectroscopy of SNRs will provide measurements of both electron and ion temperatures. When combined with higher angular resolution, the relative equilibration timescales can be determined for a range of shock velocities determined directly from expansion measurements. These measurements will provide crucial insights into heating by fast shocks.

3.2. Environmental Studies of Supernovae

Sensitive high-resolution X-ray studies of SNe will provide strong constraints on the properties of the progenitor systems. For core-collapse systems, high quality spectra will establish the nature of the X-ray emission and measure the density of the CSM and the properties of the ejecta, while imaging of Type Ia SNe will help to establish the physical nature of these explosions by distinguishing between single-degenerate and double-degenerate progenitor scenarios.

X-ray emission from young SNe is a function of the density, distribution, and velocity of both the SN ejecta and the surrounding circumstellar material (CSM), and high sensitivity X-ray observations provide the most direct probes of these quantities. About 50 young (days to years old) SNe have been seen in X-rays to date, all from core-collapse systems, but we are still in the infancy of understanding the detailed origins of this early X-ray emission. In general, the X-ray luminosities of these SNe dominate the total radiative output of the SNe starting at an age of about one year. The X-ray emission of normal Type II SNe is convincingly explained as thermal radiation ($kT \lesssim 10$ keV) from the reverse shock region that forms within the expanding SN ejecta as it interacts with the dense stellar wind of the progenitor star, and Chevalier, Fransson, & Nymark (2006) have shown how X-ray and radio measurements of Type IIP SNe are excellent probes of the mass loss of the progenitor star. The origin of Ib/c X-rays is less clear; Chevalier & Fransson (2006) have suggested an inverse-Compton+synchrotron mechanism. The Type IIn SNe are perhaps the least understood but, at late times, can be the most X-ray luminous subtype. The X-ray emission could result from the shocked ejecta, as in the case of the normal Type II SNe, or it could originate from shocked clumps of gas in the CSM; these two scenarios predict vastly different widths for X-ray emission lines, but we have not yet obtained an X-ray spectrum of sufficient quality to make the distinction.

If either the CSM density or the steepness of the ejecta radial density structure is high, the reverse shock is radiative. Models of the X-ray spectrum and the ejecta velocities are sensitive functions of the density distribution, and together they constitute unique probes of the explosion dynamics, as well as nucleosynthesis. These determinations of the CSM and ejecta properties, which could potentially also resolve different velocity components, separating emission from different layers in the ejecta, require high quality, high resolution X-ray spectra that are currently infeasible with *Chandra* and *XMM-Newton*. Typical X-ray imaging observations of young SNe have contained dozens to hundreds of counts; dispersed spectra with *Chandra* and *XMM-Newton* would be of such low S/N as to be unusable. To make substantial progress will require substantial improvements in the collecting area available to a high spectral resolution X-ray instrument.

For Type Ia SNe, whose use as standardized candles to map cosmological parameters is of particular importance, there are currently significant uncertainties in the nature of their progenitor systems. At present, the three most popular progenitor models for thermonuclear SNe Ia include (i) a white dwarf (WD) near the Chandrasekhar mass ($M_{\rm Ch}$) accreting from a non-WD companion, (ii) binary low mass WDs that eventually merge, and (iii) a sub-$M_{\rm Ch}$ WD accreting Helium from a non-WD companion onto a thick shell. While optical observations probe the recession of the photosphere into the slowest and deepest ejecta, it is the temporal and spectral evolution of the nonthermal X-ray emission that directly maps to the properties of the CSM including the density, profile, and possibly binary-induced shells, thereby constraining the properties of the progenitor systems (Dwarkadas & Chevalier 1998). Such X-ray emission falls below the detection thresholds for current X-ray instruments (see, e.g., Hughes et al. 2007).

The expected X-ray luminosity scales roughly with CSM density, which is determined by the mass loss history of the donor star and accretion rate onto the WD shape the expected X-ray light-curves. Single-degenerate models for typical SNe Ia predict CSM densities roughly comparable to the low end of the distribution inferred for core-collapse SNe (Chevalier 1984) and just below our current X-ray detection thresholds with *Chandra*. For a standard wind density profile, the X-ray emission should decay steeply ($F_X \propto t^{-1}$) beginning immediately after explosion. Lower mass loss rates (or higher wind velocities) produce even lower CSM densities at the radii probed by the fastest ejecta. Moreover, accretion onto a dense shell produces a sharp peak in the X-ray emission, visible within just days of the explosion and fading quickly thereafter.

As optical surveys improve and SNe Ia will begin to be discovered within just hours of explosion, the opportunity arises for fast Target-of-Opportunity X-ray observations to catch the fleeting X-ray signal. Improved sensitivity over existing missions is also required to get several epochs of X-ray detections and to trace the evolution of the X-ray emission with time. With a typical ToO response time of a day, *Gen-X* could probe the X-ray emission from a young SN Ia within just 1-2 days of explosion and provide the necessary sensitivity to detect even the faint X-ray signal from a double-degenerate system. High spatial resolution (less than 1 arcsec) is required to distinguish the SN from other X-ray sources in the host galaxies (e.g. CVs, ULXs). Temporal evolution over the first 10 days since explosion will distinguish between a single-degenerate WD embedded in a RSG wind (decaying X-ray signal), a double-degenerate WD system (faint, but steady or increasing signal), and accretion onto a shell (shark peak in X-ray emission).

In summary, our understanding of supernovae and their remnants has blossomed in recent decades, enabled in large part to X-ray observations. It has become clear that physics occuring on small scales drives the ultimate large-scale structure and behavior of these systems, and that we have now begun to probe this structure with observatories like *Chandra*. To understand the manner in which particles are accelerated at shocks in pulsar winds and SNRs, and to understand the environments and progenitors of the explosive events that form these systems requires development of X-ray imaging systems with angular resolution of ~ 0.1 arcsec and effective area of tens of square meters. A technology development program that lays the groundwork to provide such capabilities in the 2020 timeframe is crucial to advance our understand in these important areas.

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